Astro 205. Lecture 3 September 22, 2003

Stars

The Sun is a star, a fairly typical one as we shall see. Let's define some global properties of stars:

The **mass**: this is measured in *solar masses*, where

$$1 \ \mathrm{M}_\odot \ = \ 2 \times 10^{33} \ \mathrm{gm}$$

Stellar masses range from about 60 $\mathrm{M}_\odot$ to 0.08 $\mathrm{M}_\odot$.

The **composition**. By mass, the Sun is about 75% hydrogen, 23% helium and 1-2% everything else. The elements heavier than hydrogen and helium (and lithium, beryllium and boron) are called the *heavy elements*. The amount of an element relative to hydrogen is called its *abundance*. By and large, the abundances of the heavy elements in a star track each other, that is a star with, say a high relative carbon abundance will also have a high relative calcium abundance and so on. The composition of the Sun and other stars is thus quite different from that of the solar system planets, especially of the inner planets. Since the inner plantets are rocky, and therefore largely made of heavy elements (silicon, oxygen, aluminum, titanium, iron etc.) you might expect that stars with high heavy element abundances would be more likely to have planets. We'll take a look at this later. Stars have heavy element abundances ranging from something like twice that of the Sun down to 1/10,000 or less that of the Sun.

The element abundances in a given star can be measured by *spectroscopy* as we will see next week.

The **luminosity**. The luminosity of an object is the *total amount of electromagnetic energy radiated per unit time*. As you see from the above discussion of stellar composition, stars are large spheres of gas which radiate energy. *Electromagnetic radiation* is emitted at different wavelengths or frequencies which cover the entire *electromagnetic spectrum*.

The star's luminosity is then the total amount of radiation at all wavelengths emitted by the star per unit time and is measured in solar luminosities, $\mathrm{L}_\odot$, where

$$1 \ \mathrm{L}_\odot \ = \ 4 \times 10^{33} \ \mathrm{erg/second}$$

Stellar luminosities range from almost 10^6 $\mathrm{L}_\odot$ to less than 10^{-3} $\mathrm{L}_\odot$.

The *stellar temperature*, usually called the *effective temperature*, is the temperature of the "surface" of the star. There is no such thing, since the star is gaseous, so here's a definition. Stars produce radiation in their interior which works its way to the outside by multiple absorptions and scatterings by the stellar matter. The "surface" where the radiation can finally fly free and leave the star is called the *photosphere*, the surface from which the light is radiated. The Sun's effective temperature is about 6000 K. Here, temperature is measured in *Kelvins*, or *degrees Kelvin* = temperature in °C (degrees centigrade) + 273, i.e. Kelvins measure the temperature above absolute zero.

The **stellar radius**, the radius of the photosphere. The Sun's radius is about

$$1 \ \mathrm{R}_\odot \ = \ 7 \times 10^{10} \ \mathrm{cm}$$

For main sequence stars, shortly to be discussed, stellar radii range from about 20 $\mathrm{R}_\odot$ down to about 0.1 $\mathrm{R}_\odot$ (roughly the radius of Jupiter, and thereby hangs a very interesting tale as we shall see).

Measuring Stellar Parameters

How do we measure these basic quantities for a star? The *radius* is a very difficult quantity to measure, and we'll leave that for later. The **mass** is also difficult. We'll discuss this more carefully later, but basically you can do this the same way you measure the mass of the Sun: you measure the *period* (or *orbital speed*) and the distance from the star of a body orbiting the star, and apply the same "Kepler's Laws" analysis we used for measuring the Sun's mass. Planets would be ideal but you can't see them. Stellar masses are measured by observing the orbits of *binary stars*, i.e. pairs of stars in orbit around each other. More later.

The *luminosity* is the total amount of radiation emitted by a star at all wavelengths. What do we actually measure when we observe a star? We measure the *flux* as a function of wavelength (strictly speaking, the flux as a function of wavelength is called the flux density, but I am going to be sloppy about this), and then add it all up to get the total flux. What is flux? It's the energy flowing through a unit area per unit time. If I have a *detector* which detects flux, then I will detect more energy per unit time if I have a bigger detector. Thus flux is *energy per unit time per unit area.* More on the problems of measuring total flux below.

But the total flux does not give you the stellar luminosity: you need one more piece of information, the distance; the further away is a given object, the fainter it looks, i.e. the smaller the flux. Flux, luminosity and distance are related by the *inverse square law*:

$$\mathrm{F} = \frac{\mathrm{L}}{4\pi \mathrm{D}^2}$$

where F is the flux, L the luminosity and D the distance (for a diagram, see GO p34). This is a direct consequence of the conservation of energy. The total energy flowing through a spherical surface surrounding a source of radiation has to be the same regardless of the radius. So at two distances, D_1 and D_2, we have

$$4\pi \mathrm{D}_1^2 \mathrm{F}_1 = 4\pi \mathrm{D}_2^2 \mathrm{F}_2 = \mathrm{L}$$

(all this is why astronomers want really big telescopes - objects at astronomical distances are very faint, so to detect as much energy from the object as possible you need as big an area as possible: the signal you detect is

$$\mathrm{I} = \mathrm{AF}$$

where A is the area of your telescope).

How to measure *distance*? This is another difficult thing to do. The only direct way is by *parallax*, which is like *surveying*. You establish a baseline of known size, then from the ends of the baseline take sightings of the object whose distance you wish to measure. Since the baseline has a finite length, the directions towards the object from the ends of the baseline are at slightly different angles. Let's call the difference between the two angles θ. Then in the small-angle limit

$$\mathrm{D} = \frac{\mathrm{d}}{\theta}$$

where D is the distance to the star and d is the baseline (for a diagram, see GO p31-34). Evidently, the largest distance D you can measure depends on how small an angle θ you can measure and how large a baseline d you can define. The largest baseline to which we readily have access is the diameter of the Earth's orbit, and these days the smallest angle we can measure is a few milli-arcseconds, a few $\times$ $0.001''$ (1 degree = 60 arcminutes = 3600 arcseconds). This means we can measure distances of something like

$$\mathrm{D} = \frac{1.5 \times 10^{13}\mathrm{cm}}{\sin(0.005\mathrm{arcsec})}$$

or about 6 $\times 10^{20}$ cm, about 600 light years. This allows us to measure distances to thousands of stars, but is very small compared to the diameter of the Galaxy, about 60,000 light years.

Before we leave the subject of distance, let's define one more unit, a unit of distance. The measurement of distances by parallax gives a natural unit: the *parsec.* One parsec is the distance to a star for which the radius of the Earth's orbit (1.5×10^{13} cm) subtends 1 arcsecond. 1 parsec = 3.1 $\times10^{18}$ cm (work it out and check this) = 3.25 light years. Professional astronomers use parsecs. "Parsec" is often abbreviated "pc". Additional units are the kiloparsec (one thousand parsecs) and the Megaparsec (one million parsecs).

Electromagnetic Radiation

Electromagnetic radiation travels at the speed of light (about 3 $\times10^{10}$ cm/second). EM radiation has different *wavelengths*. Some wavelengths can get through the Earth's atmosphere, others can't.

Long wavelength radiation (meters) is called *radio radiation*. The longest wavelengths cannot reach the earth because of the radiation belts, charged particles trapped in the Earth's magnetic field. Much radio radiation can reach the Earth's surface, however. Short-wavelength radio waves are sometimes called microwaves.

At the shortest radio wavelengths, millimeter and submillimeter wavelengths, the radiation mostly cannot reach the Earth's surface because of absorption by atmospheric water vapor (think how microwave ovens work). Shorter yet is *infrared radiation*, "heat". Only the shortest IR wavelengths can get through the atmosphere. Shorter than IR is *visible* radiation, light, which does get to the Earth's surface. Next is ultraviolet radiation, absorbed by atmospheric ozone. Then Xrays and finally gamma rays, both absorbed by the atmosphere. The Earth's atmosphere thus has two "windows" at radio and optical wavelengths; everything else is blocked, At the edges of these windows, millimeter-wave and infrared, some radiation can get through, especially at very high dry sites like Antarctica or the tops of high mountains.

The energy, frequency and wavelength of EM radiation are related by

$$\mathrm{E} = \mathrm{h}\nu$$
$$\lambda = \frac{\mathrm{c}}{\nu}$$

where E is the energy, h is a constant (Planck's constant), ν is the frequency, c is the speed of light (3×10^{10} cm/sec) and λ the wavelength. If E is in ergs, λ in cm, ν in Herz (cycles/second), h = 6.6 $\times10^{-27}$ erg sec. Thus short wavelength = high frequency = high energy. The wavelengths of visible light range from about 4×10^{-5} cm (blue) to 7.5×10^{-5} cm (red) (see GO p35).

Black Body Radiation

Hot bodies radiate electromagnetic radiation. Perfect bodies, which perfectly absorb and perfectly emit electromagnetic radiation of all wavelengths, radiate a *black-body spectrum*. This is a (very roughly) triangular curve whose peak lies at a wavelength determined by the body's temperature: the higher the temperature, the shorter the peak wavelength (white-hot objects are hotter than red-hot objects). The formula for a blackbody curve is derived in the notes at the end. See also Shu p77.

Stars are pretty decent black bodies, to first order. They radiate like black bodies, and the total luminosity is related to the temperature and the surface area of the body by

$$\mathrm{L} = 4\pi \mathrm{R}^2\sigma \mathrm{T}^4$$

where L is the luminosity (ergs/sec), R the radius (cm), σ a constant, 5.7 $\times10^{-5}$ erg/cm^2/s/K^4, and T the temperature in K. The hotter a body of given radius, the more total radiation it emits and the bluer the color.

Thus if you can measure the luminosity of a star and its temperature (from a measurement of its color) you can plot one against the other and, behold, the data points do not scatter all over the place but lie along a sequence from hot stars of high luminosity to cool stars of low luminosity.

This diagram is called the *Herzsprung-Russell Diagram* or HR diagram and the sequence of points is the main sequence.

So why do stars have this range of luminosities and colors? Well, we will have to understand how they work to answer this. But just think about a couple of things: the stars (like the Sun) radiate vast amounts of energy *steadily* for billions of years (in most cases). The question is not just how do they produce so much energy, but why are they so stable? And second, if they are radiating energy into cold space, they must also be producing it. How do they do so for such long times? We'll look at this on Wednesday.